

**Few-Body Systems (APFB2011) manuscript No.**  
 (will be inserted by the editor)

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# Penta-quark states with hidden charm and beauty

Received: date / Accepted: date

**Abstract** More and more hadron states are found to be difficult to be accommodated by the quenched quark models which describe baryons as 3-quark states and mesons as antiquark-quark states. Dragging out an antiquark-quark pair from the gluon field in hadrons should be an important excitation mechanism for hadron spectroscopy. Our recent progress on the penta-quark states with hidden charm and beauty is reviewed.

**Keywords** Penta-quark states · Hidden charm · Hidden beauty

## 1 Quenched and unquenched quark models

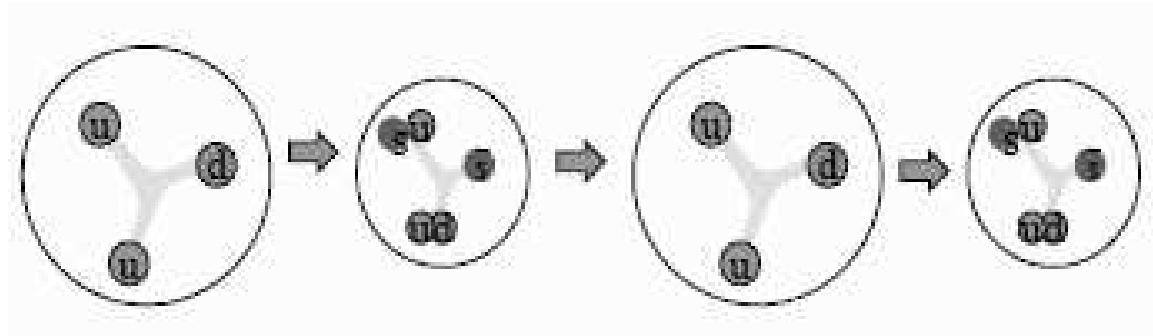
In the classical quenched quark models, all established baryons are ascribed into simple 3-quark ( $qqq$ ) configurations [1]. The classical quark models gave very good description of the mass pattern and magnetic moments for the baryon SU(3) baryon  $1/2^+$  octet and  $3/2^+$  decuplet of spatial ground states. The excited baryon states are described as excitation of individual constituent quarks, similar to the cases for atomic and nuclear excitations. The lowest spatial excited baryon is expected to be a ( $uud$ )  $N^*$  state with one quark in orbital angular momentum  $L = 1$  state, and hence should have negative parity. However, experimentally, the lowest negative parity  $N^*$  resonance is found to be  $N^*(1535)$ , which is heavier than two other spatial excited baryons:  $\Lambda^*(1405)$  and  $N^*(1440)$ . This is the long-standing mass reverse problem for the lowest spatial excited baryons.

In the simple 3q constituent quark models, it is also difficult to understand the strange decay properties of the  $N^*(1535)$ , which seems to couple strongly to the final states with strangeness. Besides a large coupling to  $N\eta$ , a large value of  $g_{N^*(1535)K\Lambda}$  is deduced [2, 3] by a simultaneous fit to BES data on  $J/\psi \rightarrow \bar{p}p\eta$ ,  $pK^-\bar{\Lambda} + c.c.$ , and COSY data on  $pp \rightarrow pK^+\Lambda$ . There is also evidence for large  $g_{N^*(1535)N\eta'}$  coupling from  $\gamma p \rightarrow p\eta'$  reaction at CLAS [4] and  $pp \rightarrow pp\eta'$  reaction [5], and large  $g_{N^*(1535)N\phi}$  coupling from  $\pi^- p \rightarrow n\phi$ ,  $pp \rightarrow pp\phi$  and  $pn \rightarrow d\phi$  reactions [6, 7, 8].

On the other hand, unlike atomic and nuclear excitations, the typical hadronic excitation energies are comparable with constituent quark masses. Hence to drag out a  $q\bar{q}$  pair from gluon field could be a new excitation mechanism besides the conventional orbital excitation of original constituent quarks. Then the mass reverse problem and the strange decay properties of the  $N^*(1535)$  can be easily understood by considering 5-quark components in them [2, 9, 10]. The  $N^*(1535)$  could be the lowest  $L = 1$  orbital excited  $|uud\rangle$  state with a large admixture of  $|[ud][us]\bar{s}\rangle$  pentaquark component having  $[ud]$ ,  $[us]$  and  $\bar{s}$  in the ground state. The  $N^*(1440)$  could be the lowest radial excited  $|uud\rangle$  state with a large admixture of  $|[ud][ud]\bar{d}\rangle$  pentaquark component having two  $[ud]$  diquarks in the

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**Fig. 1** The breathing mode of  $qqq \leftrightarrow qqqq\bar{q}$  for the lowest  $1/2^-$  baryon octet.

relative P-wave. While the lowest  $L = 1$  orbital excited  $|uud\rangle$  state should have a mass lower than the lowest radial excited  $|uud\rangle$  state, the  $|[ud][us]\bar{s}\rangle$  pentaquark component has a higher mass than  $|[ud][ud]\bar{d}\rangle$  pentaquark component. The lighter  $\Lambda^*(1405)1/2^-$  is also understandable in this picture. Its main 5-quark configuration is  $|[ud][us]\bar{u}\rangle$  which is lighter than the corresponding 5-quark configuration  $|[ud][us]\bar{s}\rangle$  in the  $N^*(1535)1/2^-$ . The large mixture of the  $|[ud][us]\bar{s}\rangle$  pentaquark component in the  $N^*(1535)$  naturally results in its large couplings to the  $N\eta$ ,  $N\eta'$ ,  $N\phi$  and  $K\Lambda$ .

A breathing mode of  $qqq \leftrightarrow qqqq\bar{q}$  is proposed [11, 12] for the lowest  $1/2^-$  baryon octet as shown in Fig.1. Each baryon is a mixture of the three-quark and five-quark components. The two components represent two different states of the baryon. The  $qqq$  state with  $L = 1$  and higher kinetic energy has weaker potential; when quarks expand, a  $q\bar{q}$  pair is dragged out and results in a  $qqqq\bar{q}$  state with  $L = 0$  and stronger potential; the stronger potential leads  $qqqq\bar{q}$  state shrinking to a more compact state which then makes the  $\bar{q}$  to annihilate with a quark easily and transits to the  $qqq$  state with  $L = 1$  and more kinetic energy to expand; this leads to constantly transitions between these two states. The five-quark component has a smaller size than the three-quark component and results in a much flatter  $Q^2$ -dependence for the  $\gamma^*N \rightarrow N^*(1535)$  transition where  $\gamma^*qqq \rightarrow qqqq\bar{q}$  plays a very important role [11, 12].

Besides the penta-quark configurations with the diquark correlation, the penta-quark system may also be in the form of meson-baryon states. The  $N^*(1535)$ ,  $\Lambda^*(1405)$  and some other baryon resonances are proposed to be meson-baryon dynamically generated states [13, 14, 15, 16, 17, 18, 19].

Quenched  $qqq$  quark models and unquenched  $qqq \leftrightarrow qqqq\bar{q}$  quark models give very different predictions for the  $1/2^-$  SU(3) nonet partners of the  $N^*(1535)$  and  $\Lambda^*(1405)$ . While quenched quark models [20] predict the  $1/2^- \Sigma^*$  and  $\Xi^*$  to be around 1650 MeV and 1760 MeV, respectively, the unquenched quark models [9, 10, 12] expect them to be around 1400 MeV and 1550 MeV, respectively, and meson-baryon dynamical models [21, 22, 23] predict them to be around 1450 MeV and 1620 MeV, respectively.

Although various phenomenological models give distinguishable predictions for the lowest  $1/2^- \Sigma^*$  and  $\Xi^*$  states, none of them are experimentally established. There is a  $1/2^- \Sigma^*(1620)$  listed as a 2-star resonance in the PDG tables [1]. However, a recent analysis [24] of the new Crystal Ball data [25] on the  $K^-p \rightarrow \pi^0\Lambda$  reaction with the  $\Lambda$  polarization information indicates that the  $1/2^- \Sigma^*(1620)$  is not needed by the data while the  $1/2^+ \Sigma^*(1635)$  is definitely needed. The data of differential cross sections for this reaction without  $\Lambda$  polarization information cannot distinguish the  $1/2^-$  and  $1/2^+$ . This may be the reason that some previous analyses claimed the observation of the  $1/2^- \Sigma^*(1620)$ . Instead some re-analyses [26, 27, 28] of the  $\pi\Lambda$  relevant data suggest that there may exist a  $\Sigma^*(1/2^-)$  resonance around 1380 MeV, which supports the prediction of unquenched quark models.

To pin down the nature of the lowest  $1/2^-$  SU(3) baryon nonet, it is crucial to find hyperon states of the lowest SU(3)  $1/2^-$  nonet and study their properties systematically. It would be very useful to systematically analyze the available data on  $KN \rightarrow KN$ ,  $\pi\Lambda$ ,  $\pi\Sigma$  reactions and relevant  $\psi$  decay channels, including the new data from the Crystal Ball Collaboration [25] and BESIII Collaboration.

## 2 Prediction of superheavy $N^*$ and $\Lambda^*$ states with hidden charm and beauty

Although many  $N^*$  and  $\Lambda^*$  resonances were proposed to be meson-baryon dynamically generated states or penta-quark states, none of them can be clearly distinguished from qqq-model states due to tunable ingredients and possible large mixing of various configurations in these models. A possible solution to this problem is to extend the penta-quark study to the hidden charm and hidden beauty sectors. If the  $N^*(1535)$  is the  $\bar{K}\Sigma$  quasi-bound state with hidden strangeness, then naturally by replacing  $s\bar{s}$  by  $c\bar{c}$  or  $b\bar{b}$  one would expect super-heavy  $N^*$  states with hidden charm and hidden beauty just below  $\bar{D}\Sigma_c$  and  $B\Sigma_b$  thresholds, respectively.

Following the Valencia approach of Ref.[29] and extending it to the hidden charm sector, the interaction between various charmed mesons and charmed baryons were studied with the local hidden gauge formalism in Refs.[30, 31]. Several meson-baryon dynamically generated narrow  $N^*$  and  $\Lambda^*$  resonances with hidden charm are predicted with mass around 4.3 GeV and width smaller than 100 MeV. The S-wave  $\Sigma_c\bar{D}$  and  $\Lambda_c\bar{D}$  states with isospin  $I=1/2$  and spin  $S=1/2$  were also dynamically investigated within the framework of a chiral constituent quark model by solving a resonating group method (RGM) equation by W.L.Wang et al. [32]. They confirm that the interaction between  $\Sigma_c$  and  $\bar{D}$  is attractive and results in a  $\Sigma_c\bar{D}$  bound state not far below threshold. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks. Because these predicted states have masses above  $\eta_c N$  and  $\eta_c \Lambda$  thresholds, they can be looked for at the forthcoming PANDA/FAIR and JLab 12-GeV upgrade experiments. This is an advantage for their experimental searches, compared with those baryons with hidden charms below the  $\eta_c N$  threshold proposed by other approaches [33, 34].

The same meson-baryon coupled channel unitary approach with the local hidden gauge formalism was extended to the hidden beauty sector in Ref.[35]. Two  $N_{b\bar{b}}^*$  states and four  $\Lambda_{b\bar{b}}^*$  states were predicted to be dynamically generated. Because of the hidden  $b\bar{b}$  components involved in these states, the masses of these states are all above 11 GeV while their widths are of only a few MeV, which should form part of the heaviest island for the quite stable  $N^*$  and  $\Lambda^*$  baryons. For the Valencia approach, the static limit is assumed for the t-channel exchange of light vector mesons by neglecting momentum dependent terms. In order to investigate the possible influence of the momentum dependent terms, the conventional Schrodinger Equation approach was also used to study possible bound states for the  $B\Sigma_b$  channel by keeping the momentum dependent terms in the t-channel meson exchange potential. It was found that within the reasonable model parameter range the two approaches give consistent predictions about possible bound states. This gives some justification of the simple Valencia approach although there could be an uncertainty of 10 - 20 MeV for the binding energies.

Production cross sections of the predicted  $N_{b\bar{b}}^*$  resonances in  $pp$  and  $ep$  collisions were estimated as a guide for the possible experimental search at relevant facilities in the future. For the  $pp \rightarrow pp\eta_b$  reaction, the best center-of-mass energy for observing the predicted  $N_{b\bar{b}}^*$  is  $13 \sim 25$  GeV, where the production cross section is about 0.01 nb. For the  $e^-p \rightarrow e^-p\gamma$  reaction, when the center-of-mass energy is larger than 14 GeV, the production cross section should be larger than 0.1 nb. Nowadays, the luminosity for  $pp$  or  $ep$  collisions can reach  $10^{33} cm^{-2}s^{-1}$ , this will produce more than 1000 events per day for the  $N_{b\bar{b}}^*$  production. It is expected that future facilities, such as proposed electron-ion collider (EIC), may discover these very interesting super-heavy  $N^*$  and  $\Lambda^*$  with hidden beauty.

Very recently, the observation of the iso-vector meson partners of the predicted  $N_{b\bar{b}}^*$ ,  $Z_b(10610)$  and  $Z_b(10650)$ , were reported by Belle Collaboration [36]. This gives us stronger confidence on the existence of the super-heavy island for the  $N_{b\bar{b}}^*$  and  $\Lambda_{b\bar{b}}^*$  resonances.

**Acknowledgements** I thank C. S. An, P. Z. Gao, F. Huang, R. Molina, E. Oset, W. L. Wang, J. J. Wu, L. Zhao, Z. Y. Zhang for collaboration works reviewed here. This work is supported by the National Natural Science Foundation of China (NSFC) under grants Nos. 10875133, 10821063, 11035006 and by the Chinese Academy of Sciences under project No. KJCX2-EW-N01, and by the Ministry of Science and Technology of China (2009CB825200).

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